Some Aspects of Powder Metallurgy

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Introduction

THIS correlated review is an attempt to present some of the more common aspects of the powder metallurgy process in order to acquaint telephone engineers with an increasingly important production method, and to provide an outline of topic references that could otherwise be obtained only from many different sources.

Basically, the art of powder metallurgy deals with the preparation of metal powders and their utilization. This is a general description, however, and covers not only the metallurgical field, but also the paint and pigment and other more strictly chemical industries. As a more pertinent definition, the following has been suggested: "Powder metallurgy is the art of producing metal powders and shaped objects from individual, mixed, or alloyed metal powders, with or without the inclusion of non-metallic constituents, by pressing or forming objects which are simultaneously or subsequently heated to produce a coalesced, sintered, alloyed, brazed, or welded mass, characterized by the ahsence of fusion, or the fusion of a minor component only"[1].

In the past few years, powder metallurgy has received considerable attention, not only in technical publications, but also in the newspapers and popular periodicals, the general implication of the latter being that a completely new and revolutionary field of metallurgical endeavor has been uncovered. Actually, however, instead of something new, we are dealing with an art that had its inception at the time man first started using metals; numerous examples exist today of the early attempts to produce solid articles from metal powders. It is not surprising that early investigators and workers dealt with powders rather than massive structures of metals. With the exception of a few low melting metals such as tin and lead, most of the metals available melted at temperatures above those which could be attained at the time with crude furnace equipment. It was possible, however, to prepare powders of many metals by rather simple means without extensive furnace equipment, and a number of such powders were produced. Iron, for example, was reduced from its ores and worked to solid form at least 5,000 years ago, long before furnaces were devised which could even approach the melting point of the metal. The resulting reduced product was not, of course, massive iron, but was a sponge powder material which

could be compacted, heated, sintered, and forged in mucb the same manner that metal powders are treated today. An outstanding example of the massive pieces produced by such methods is the $6\frac{1}{2}$ ton Delhi pillar made about 1,600 years ago[2].

History of Development

The ancient Egyptians and probably other early civilizations discovered how to make powders of gold, silver, copper, bronze, iron, lead, and to a limited extent, tin, antimony, and platinum[3], but it was necessity rather than desire wbich led these early workers to produce tbeir massive metal tools, ornaments, and weapons by powder metbods. It is interesting to note that as furnaces were devised to obtain higher temperatures, the list of metals prepared from powders decreased. Tbe lower melting metals, of course, were the first to be prepared by melting and casting methods, and as higber temperatures were attained, only the more bigbly refractory metals remained on tbe powder preparation list.

Althougb iron had been known in prehistoric days, it remained a scarce, precious metal for several thousand years, and did not come into general use until introduced by the Hittites around 1300 B.C. The Hittites presumably mined iron ore in the iron region along tbe Black Sea in Asia Minor and worked the material to metal form[4]. By 100 B.C., the use of iron had spread westward to include many of the countries bordering the Aegean and the Mediterranean. The primitive methods of iron working probably consisted in heating the iron ore in a charcoal fire fanned by an air hlast from a bellows until reduction of the oxide was attained. The spongy mass was then pressed, beated, and forged to the desired shape.

That this was tbe general practice followed in many countries in the production of metal objects has been observed from articles unearthed from earlier civilizations. Somewbat similar methods of working other metals have heen observed, and where difficulty was experienced in obtaining sintering, other metal powders were added that were lower melting themselves, or that formed lower melting alloys which wet and welded together the particles of metal being worked to form a lump that could be shaped. The Incas in South America used such a method in fabricating many small articles of platinum[5]. The grains of native platinum were mixed with some gold and silver, and, by means of a hlow-pipe, were fritted together hy the lower melting alloy of gold and silver. The resulting mass could then be forged to the desired shape.

During the eighteentb century there was a fair amount of activity in the production of metal powders, and in studies of the fabrication of metal parts from tbe powders. Platinum was introduced into England in 1741 and attempts were made to produce the metal in compact usable form[3].

Various expedients were used, and one which utilized a unique principle is worthy of note.

It was observed about the middle of the century that platinum would fuse at relatively low temperatures in the presence of arsenic[3], and that, on prolonged heating, the arsenic could be volatilized out of the fused lump to leave behind a sponge of metallic platinum. This sponge could then be beated and forged to solid form. Similar results were obtained using mercury* or sulphur in place of arsenic; and the success of the forging methods led other investigators to study the welding of grains of native platinum or platinum scraps without the use of added elements to lower the fusion point.

Such was the situation in the early part of the nineteenth century when Wollaston[7] developed his method for the preparation of platinum ware. Numerous other investigators[3,6,8] had produced articles of platinum by treatment of finely divided platinum or sponge, but by careful refinements in the process with control of particle size, purity, compacting pressure and sintering treatment, Wollaston obtained a superior product. Precautions were taken to use only the more finely divided platinum particles, and to press the powder carefully in a mold while wet. This pressing of wet powder is claimed to have been one of the main contributions made by Wollaston since a much lower compacting pressure was allowable, and the particles were not work hardened. The resulting cake was then slowly dried to remove volatile matter and adsorbed gases before sintering at 800°–1000° C. The material was forged while still hot, and gave the first really pure, blister-free platinum sheet. That the process developed by Wollaston was sound is shown by the fact that the platinum produced by powder metallurgy at present in England is made by essentially the same procedure[21]. The careful studies made by Wollaston in fabricating platinum ware of high purity thus led to the basic principles utilized in successfully producing massive metal parts from metal powder.

During the nineteenth century, many metals were produced in powder form, but there seems to have been no correlated effort to convert the powders into coherent form. This may have been due to the development of better melting furnace equipment that allowed ordinary melting and casting techniques to be employed for most metals and alloys. On the other hand, there remained some of the more refractory metals such as tungsten, tanta-

* As an example of how new methods introduced can often be traced back to earlier sources, the use of mercury to form an amalgam which could then be heated to leave a powder sponge material, has been attributed to the monk Theophilus in the 11th century[8]. In this case, the amalgam process was used with gold, and the end product sought was gold powder which could be used as a pigment in inks for illuminating manuscripts. There was no attempt, however, to carry the process further to make solid metal parts as was the case with platinum as cited above.

lum, molybdenum, osmium, and iridium which could have been treated in much the same manner as in Wollaston's process for platinum.

There were, however, instances where real effort was made to develop useful products by means of powder metallurgy. As early as 1870, the fundamental idea of a self-lubricating bearing was disclosed in a patent by Gwynn[9] and was the prototype for a large number of later developments in the field. To 99 parts of tin prepared by rasping or filing, one part of petroleum still residue was added, and the mass heated and intimately mixed. The mixture was then pressed to give the shape and solidity desired. It was specifically stated by Gwynn that journal boxes made by this method or lined with the material would allow shafts to run at high speed without other lubrication[10].

There were a number of metal powder producers in the nineteenth century, most of them producing flake powders, but a virtual monopoly in the field was held by Sir Henry Bessemer from about 1840 to 1885, when he retired from the business[11]. The process was a secret one and remained so for almost his entire business career, and the profits were so large that they financed the development of the Bessemer process for making steel. Essentially, the method was one of machining very fine filaments from solid metal bars and passing the filaments through rolls to flatten and break them into flat tabular particles. Precautions were taken to prevent sticking and give a high polish to the powder by adding a very small amount of olive oil. The powder was graded by means of an air blast in a tunnel about 40 feet long and $2\frac{1}{2}$ feet wide, the finest powder fraction being collected in silk bags attached to the end of the tunnel. Bessemer's powder metals included copper, and most of the common alloys of copper.

Even with the relatively large scale production of flake metal powders by Bessemer up to 1885, and the subsequent preparation of powder metals by stamp mills which pulverized the metal by severe working, there was very little actual commercial manufacture of solid compacts from powder metals.

The electric lamp industry provided the stimulus for further study in the search for a metallic filament to replace the carbon filament first used. This culminated in the production of the tungsten filament[10,12] and indicated the technique to be applied in the development of the other refractory metals as well as the production of cemented carbides, electrical contacts, and electrode materials.

Even with the promise shown by this development and the production of other ductile heavy metals, there was little other commercial activity in powder metallurgy as late as 1915–1920.

Various types of porous bearings had received sporadic attention, and, in 1921, a new porous bronze bearing was described[13]. The material was

a bronze having finely divided graphite uniformly distributed throughout the mass. It was prepared by mixing the oxides of tin and copper with graphite, compressing the mass and heating. There was reduction of the oxides by the graphite and partial diffusion of the copper and tin to give a porous bronze structure in which excess graphite was uniformly distributed in amounts as high as 40 per cent by volume. In addition, there was sufficient porosity for the introduction of 2 to 3 per cent of oil. Later developments utilized the metal powders rather than the oxides[14], and porous bearings in a variety of compositions and forms have constituted a large part of the total production of powder metallurgy products over the years. Of considerable influence on the design and utilization of this type of bearing has been the demand by the automotive industry for large quantities of small bearing parts. Many of these parts are at inaccessible places, and the value of a self-lubricating surface is apparent. As suggested previously, these bearings are not all of the simple pressed porous alloy structure described, but many are complicated such as those having a steel backing coated with a porous sponge alloy of copper-nickel in which the voids are impregnated with Babbitt metal[15].

A later development, and one which has had tremendous industrial significance, was the production of cemented carbides[17,18,19] and their use in cutting tools, dies, and hard surfaced parts of many types. Essentially these consist of finely divided tungsten carbide particles bonded by cobalt, or in some few instances, nickel or iron. Other carbides such as those of tantalum, titanium, or columbium may be added to impart special properties.

Powder metallurgy is admittedly an art that has progressed more rapidly than the science, but the gap is being closed by investigations of a fundamental nature. Much of the lack of correlated information in the field has been due, in part, to an understandable reluctance of the manufacturers to divulge information on their processes to competitors, and largely, as well, to the narrow specialized uses that apparently discouraged a general systematic investigation of the problems involved. Within the past ten or fifteen years, mainly through the efforts of producers of metal powders, research of a fundamental nature has been stimulated. Another factor has been the large scale adoption of the powder metallurgy process by the automobile industry for use in the preparation of many different parts. The field is still narrow and specialized, but the art has progressed to the point where powder metal parts are competing, in some instances, with parts made by the standard melting, casting, and machining procedures.

As in many similar situations where rapid expansion has occurred, there has been a tendency, not as yet based on actual performance, to oversell the product. This is a sign of healthy activity on the part of the exploiters

in the field, but a somewhat unwise course for industry as a whole to pursue. That there are limitations to powder metallurgy and many serious problems unsolved, is generally now recognized, and there is a tendency toward more conservative evaluation of the potentialities of tbe process.

It is the purpose of the remainder of this article to describe some of the common methods of preparing metal powders, to explain the fundamental principles involved in powder metallurgy, to describe the advantages and limitations of the process, and to indicate the type of product that may he expected.

Manufacture of Metal Powders

Metal powders are made in a variety of ways, each method of preparation heing suited to the metal being treated or to the end product desired. Experience has shown that no one type of metal powder can serve all the projected uses in industry, so it is not surprising that there have been developed numerous methods for the preparation of metal powders, each of which has advantages for certain types of work, and which may or may not be suited for other uses[11,16]. Listed below are some of the common methods which have been developed for producing metals and alloys in powder form. No attempt is made here to discuss these methods in detail or to point out the relative hazards[20] involved in the various processes. It is worthy of note, however, that many metal powders in a finely divided state have such a large surface area in proportion to their hulk that they are usually suhject to rapid oxidation, so rapid in many instances that they constitute an explosion hazard. Care must therefore he exercised throughout in the preparation of these powders, and many must be prepared and stored in inert atmospheres.

1. *Machining*

Machining of metals to produce powder has heen mentioned ahove in connection with the process of Bessemer. A relatively coarse powder is produced. The cost of production is usually high, and the powder use is limited to a few special applications such as dental alloys where no fines or dust are allowahle, and where the high cost of the alloy itself justifies the extra cost of this method.

2. *Milling*

By the use of various types of mills such as stamp mills, jaw crushers, gyratory crusbers, impact, and hall mills, both brittle and malleahle metals can be reduced to powder. The friable metals tend to produce angular, jagged, particles of irregular shape while the malleable metals usually produce flakes. Because of the luhricant necessary with malleable metals

to prevent the flakes from welding together, this type of powder is not greatly used for molding metal parts. The grease or other lubricant interferes with proper sintering, and there is an additional disadvantage of flakes in that low strength laminated or layered structures result in the pressing operation. The flake powders are more generally used as pigments in the paint industry where their flat surface is an asset for good coverage.

A special type of mill, the Eddy Mill, can be used for malleable metals to give particles of suitable shape, fineness, and purity for the manufacture of sintered briquettes. Essentially, the mill consists of a chamber wherein are mounted two fans facing one another and operating at high speeds in opposite directions. The metal is introduced into the chamber in relatively small pieces, (e.g. $\frac{1}{4}$–$\frac{1}{2}$ inch lengths of 0.05 inch diameter wire) which, by collision with one another in the fan blasts, become very finely pulverized. The process can be accurately controlled and a variety of shapes, angular, flake, or pebble, can be produced as desired.

3. *Shotting*

Metal shot can be prepared by dropping the molten metal from a small opening through air or an inert atmosphere into water. If the method is controlled properly, a fairly fine shot can be produced. On the whole, however, this process in powder metallurgical work is confined largely to preparing intermediate size particles for further reduction by other methods.

4. *Atomization*

For metals having relatively low melting points, atomization provides a convenient method of producing fine particles. The molten metal is forced through a small nozzle orifice and broken up by a stream of compressed air, steam, or inert gas. The process can be controlled rather closely by proper choice of nozzle, pressure and temperature of the gas used, and the rate of metal flow. As a rule, it is applied to metals melting below 700° C. such as lead, lead alloys, zinc, and aluminum; but copper, having a much higher melting point, has also been successfully treated in this manner. The product can be drawn off and collected in standard dust collector systems, and is suitable for many types of powder compacting.

5. *Carbonyl Process*

Both nickel and iron under suitable temperature and pressure conditions will react with carbon monoxide to form the respective carbonyls[22]. From these carbonyls, the metals can be obtained by a reverse of the process, decomposing the compound to the metal and the monoxide. The virtue of the process lies in the shape of particle, which appears to be almost

spherical, the purity, and the control which can be exercised in particle size. The method has been used for years in tbe Mond process for making nickel shot, hut, until recently, foreign producers exercised almost a complete monopoly on the manufacture of fine powders from carhonyl. Within the last few years, iron carbonyl powder has been produced on a large scale in this country in several different grades suited to industrial needs. The iron powder is a specialty product commanding a higber price than that produced by most other methods, hut hecause of superior properties it has been used extensively in the electrical industry, particularly in the communications field for various types of magnetic cores.

6. *Condensation of Vapor*

Metals which have low boiling points can be vaporized and the vapor then condensed in powder form. These include zinc, magnesium, and cadmium. The powders so produced are used mainly in the chemical industry.

7. *Reduction of Chemical Compounds*

Metal powders whose characteristics can be varied over a wide range are prepared in large quantities by reduction of compounds of the metal with hydrogen or other reducing gases at temperatures below the melting point. The oxide of the metal is most generally utilized for the purpose, and among the metals produced are copper, nickel, iron, cobalt, molybdenum, and tungsten. Tbe type and shape of the metal powder is governed somewhat by the compound from which it is reduced, so that, within limits, these factors are controllahle by proper choice of compound.

8. *Electrolytic Deposition*

Metals can be electrodeposited in several ways to obtain powder depending upon the plating conditions. A hard, brittle deposit may be obtained which can be further crushed or ground to small particles, or a soft sponge, or even the metal in powder form can be produced. The powder is usually dendritic in shape and requires further treatment for use in molding. This generally comprises some sort of milling or grinding operation, and an annealing treatment to eliminate hydrogen and soften the powder.

9. *Other Methods*

Other methods for the preparation of metal powders include chemical precipitation, granulation, alloy formation and removal of an alloying constituent (such as platinum-arsenic, platinum-mercury, and gold-sulphur previously discussed), and the hydride process[67]. The last mentioned method is probably tbe only one of these whicb is of more than academic interest for powder metallurgy uses.

Hydrides can be formed of many metals, those of titanium, zirconium, thorium, hafnium, columbium, and tantalum being of particular interest since they are reported to be stable at room temperature. They are produced in 300 mesh size or finer, have the appearance of metal, and begin to dissociate into hydrogen and the pure metal in vacuum or non-oxidizing atmospheres above 350° C. The hydrides can be mixed with other metal powders, and, when compacted and sintered, slowly release hydrogen which creates a protective atmosphere around the metal particles and sometimes acts to remove oxide films already present.

Despite the number of methods known for producing metal powders, the bulk of the powders used on a large scale are produced by only three methods[23]: electrolytic deposition, atomization, and reduction of metal salts by gases. The carbonyl process produces a specialty product as does the hydride process, and, while both have their uses, the amount consumed is probably small in relation to that prepared by the other methods.

The Powder Metallurgy Process

As has been indicated in the introduction, there are a number of definite steps in the powder metallurgy process which may be summarized as follows:

1. Selection of the powder or powders best suited for production of the part under consideration.
2. Proper mixing. (If more than one type of powder is being used)
3. Pressing. (Sometimes followed by pre-sintering)
4. Sintering. (Sometimes followed by an impregnating operation)
5. Coining or Sizing operation if necessary.

Each of these important operations is discussed in somewhat more detail below:

1. *Selection of Powder*

When the actual metal or alloy composition has been decided upon, there are a number of factors which must be considered in the selection of the type of powder itself. An essential characteristic is purity[23] because in the powder metallurgy process impurities cannot be slagged off as in most melting processes, and may interfere with pressing and sintering operations. Oxide films, for example, may prevent good contact between metal particles. Clean surfaces are essential if ductility, and high tensile and shear strength are required in the finished article. In most cases, there is a definite limit set for objectionable impurities in a given powder, but in some instances materials normally classed as impurities are deliberately added to obtain a desired result. An example is the addition of thorium

dioxide to tungsten as later described in the section on types of metal powder products.

The physical properties of the metal powders are also determining factors in their selection. These include particle shape, size, hardness, particle size distribution, flow characteristics, apparent density of loose powder, and particle grain structure.

Particle shape and size are governed largely by the method of production of the powder as has been suggested previously. The carbonyl process yields spherical particles, for example, while other methods produce particles that are angular, acicular, spongy, flat, rounded, granular, dendritic or otherwise irregular.

The hardness depends largely upon the metal itself, its purity, and the method of preparation. Hardness, in addition to shape of the particle, will be reflected in the amount of pressure required to obtain a given density in a finished part, and is a factor in the economics of die cost because of its influence on die life.

Particle size distribution in a metal powder is of great importance although no particular specification can be set up at present. The problem of size distribution and shape has been treated in some detail by W. D. Jones[24] and others, especially as concerned with interstitial volume or porosity. If all particles were cubes of the same size and could be placed in perfect order with the cube faces matching identically, there would be a minimum of porosity in the powder and in the pressed part. This is obviously impossible of attainment. In practice, packing is not systematic, but random, and even if identically sized cubes could be obtained, the voids between particles would be appreciable. In addition to the porosity resulting from the random packing, there are cavities which are due to bridging action of the particles themselves. This bridging is not due to irregular or angular particle shape, but can occur quite easily with spherical particles. Shaking or compressing the powder tends to destroy the bridges or arches and allow denser packing. As the powder is shaken down there is rotation of particles until corresponding surfaces come in contact and relatively dense packing is obtained. Such a rotation may not be present, however, during the rapid stroke in a die, and the particles cannot seek corresponding surfaces. In this case, there is a deformation of the particles pressed against one another so that there may be an actual keying, and the smaller particles may be pressed into the voids to produce the same result of denser packing. With a distribution of particle size, the voids between larger particles can be filled with smaller particles and, in practice, that is what is sought. The problem of setting up specified sizes or particle size distribution for powder metallurgy methods is not easy, however, because of practical complications arising in the pressing and sintering operations. Pore size

rather than total porosity then becomes the problem, since, in sintering, only the smaller pores may become closed. At present, the manufacturer of metal powders cannot guarantee his particle size distribution, nor can the user determine and specify exactly what he needs. The grades can be approximated, only, and the types required must be determined in an empirical manner[23].

The apparent density (or loading weight) is the ratio of weight in grams to volume in cubic centimeters of powder, measured according to some specified method of filling a designated receptacle. It is of considerable practical importance since it has effect on several of the operations of powder metallurgy, especially that of pressing the compact. The lower the apparent density of a powder as compared with the actual density of the solid metal, the greater will be the volume of powder required to produce a briquette of given size. This necessitates deeper dies and longer plungers than for denser materials, and for very low apparent densities may become a serious design problem. Powders can usually be supplied in a range of densities, and the proper powder selected for use. For proper blending and mixing of different metal powders for producing solid metal parts, it is advisable to select grades having comparable apparent densities. An example of the use of a low-density copper powder may be cited. For the manufacture of starting brushes in the electrical industry, copper powder and carbon powder are mixed together and compressed. By using copper powder of a low apparent density, approaching that of the carbon (1.2), good blending is assured and the danger of segregation eliminated[23].

Low rate of flow of metal powders interferes with automatic pressing operations and may make it necessary to install vibrating equipment on the feeder hopper or even on the die itself. Rate of flow is influenced by particle size distribution, particle shape, and amount of absorbed moisture.

2. *Mixing*

When only one metal is to be pressed and sintered, there is usually no necessity for mixing since the powder as received from the manufacturer is generally well blended. Where several batches of the same metal of different particle size distribution are to be added, or where different metal powders are to be used, it is necessary to mix them thoroughly prior to pressing and sintering. This may be done in any of the standard type mixers with the precaution, in some instances, of providing against oxidation of the powders.

3. *Pressing*

For preparation of the compacts, the pressing operation may be done at either ordinary or elevated temperatures. The majority of parts pro-

duced, however, are pressed at room temperature. The presses[25,26] which now are designed primarily for this type of work may be of the mechanical or hydraulic types for high production rates with modifications for rapid plunger strokes as required.

The dies are generally of hardened steel having the inner surfaces highly polished by lapping with polishing rouge in the direction of the plunger stroke so that any fine scratches that remain are in the direction of ejection of the pressed part[26]. In some instances where parts are made from highly abrasive particles, the dies are made of or lined with hard carbide materials. Die depth depends upon the apparent density of the powder being pressed, but the usual ratio of depth to part thickness is approximately 3 to 1. The greater die depth required for powders of lower density introduces the complications of friction at the die sides, unevenness of pressure distribution, and internal friction of the powder itself. There is almost no lateral flow in the powder mass, a condition which limits the shapes that can be pressed.

Pressure used varies from 5 to over 100 tons per square inch, in general, and is an important factor in limiting the size of parts that can be made by the powder process.

Following pressing, a powder compact may sometimes be given a pre-sintering treatment below the normal sintering temperature in order to increase its strength to facilitate handling, or to remove lubricants or binders which might cause difficulties later.

4. *Sintering*[24,27,28]

Sintering is the fundamental process in powder metallurgy whereby solid bodies are bonded by atomic forces.

Theoretically it is possible to obtain bonding by bringing the powder particles into so close contact with one another that the atomic forces of cohesion may become operative. But this occurs only when the respective atoms of such adjacent particles are distant in the order of magnitude of the crystal interatomic spacings; this is a condition against which there are many obstructions. Visually and even microscopically smooth particles have surfaces which are extremely jagged with respect to interatomic spacings and crystal planes. Then not large, flat areas representing large numbers of atoms, but only successive points representing relatively very small groups of atoms can be brought into sufficiently intimate contact. Moreover, even this small contact may be reduced by the presence of oxide films.

An increase of pressure will improve the bonding of such powders since the particles are deformed and pressed against one another to give increased surface contact. At the same time, rupture of the oxide films may occur with subsequent closer contact of the metal particles. This is the

general case for pressed powder compacts, or "green compacts" as they are designated. There is frequently a surprising strength associated with such pressed parts but, on the whole, a heat treatment is necessary to produce a material approaching the strength and solidity of a cast or wrought metal part.

The heating of pressed powder briquettes is usually done in an inert, reducing, or neutral atmosphere, or in vacuum. The temperature used is determined by the metal powders comprising the compact, and by the properties desired in the final product. The melting point is not exceeded for any of the components of the mixture except in those instances where such fusion of a minor constituent is desired, as, for example, in the production of cemented carbides. No definite temperature may be set for the heat treatment, but general practice is to treat at a temperature about two-thirds that of the melting point of the metal or alloy being fabricated. Higher temperatures are frequently used, however, and may be only slightly below the melting point.

The effect of heat is possibly that of causing increased surface diffusion and plasticity. The atoms on the surface of metal particles possess considerable mobility far below the melting point, and the surface energy at elevated temperatures may be appreciable. Where particles are in contact surrounding a void, flow of metal is in such a direction as to increase the area of contact.

When the sintering temperature is within the recrystallization range of the metal or metal alloy powder being treated, marked structural changes may occur. Recrystallization takes place at sites of plastic strain. Since these sites are regions of contact between particles, new crystallites form and grow into the adjacent particles so that a new series of grain boundaries is formed. The numerous cavities or voids present in the structure are not completely filled in or sealed in this operation. This could not occur without change of overall dimensions of the compressed mass. The voids may be present at the new boundaries or even enclosed in the crystallites, and produce a non-homogeneous sintered metal of relatively weak structure susceptible to sudden shock. By a high temperature treatment just below the melting point, or by alternate working and annealing, the voids can be closed and the metal consolidated to a dense, strong mass.

Surface oxide films which interfere with the sintering operation may sometimes be destroyed by treatment of the powder compact in a reducing atmosphere. If the oxide cannot be reduced in this manner, the pure metal can only be obtained by sintering operations if the oxide has a higher vapor pressure than the metal[29].

Gases, eitber adsorbed, dissolved, entrapped, chemically bound, or

resulting from chemical action, may interfere with sintering and the general rule is to avoid them if possible in attempting to produce solid metal.

Following sintering, there is sometimes a treatment for impregnating a porous structure with some material designed to confer special properties on the compact. Pressed and sintered bearings may, for example, be impregnated with oil, and a strong, porous network of tungsten may be impregnated with copper by suitable means to produce spot and line welding electrode material having high compressive strength associated with good heat and electrical conductivity.

5. *Coining or Sizing*

Although the dimensional tolerances of sintered metal parts can be rather closely controlled, it may be advantageous to control final size and improve surface structure by a coining operation consisting in re-pressing the compact in a die of suitable size.

The Modern Field of Powder Metallurgy

Most of the developments and uses of metal powders described thus far, it should be noted, have been concerned with products which could not be produced in any other way than by powder metallurgy processes. This, in fact, has been the principal field of powder metallurgy. Porous bearings with uniformly distributed porosity could not possibly be fabricated by any of the standard melting and casting techniques, nor could the carbide cutting tools be likewise manufactured.

In general, the powder metallurgy process has been applied under conditions as outlined below[30,31,32]:

1. Production of refractory metals such as tungsten, tantalum, columbium, and molybdenum.
2. Development of structures not practical by other methods. These include telephone and radio cores, and articles requiring uniform or controlled porosity such as porous bearings and metallic filters.
3. Preparation of metals to include uniformly distributed non-metals.
4. Preparation of samples comprising a metal with another metal or metals which would be immiscible in the molten state, or which do not form alloys.
5. Preparation of samples of two or more metals where one component has a low boiling point.
6. Fabrication of products that can be made more economically by the powder process than by other methods[14].

Considerable work has been done by the automotive industry and others

in developing products from powder metals that fall into class 6 above. There are many instances where automatic pressing and continuous annealing operations on small parts in quantity have made the process economically feasible for competition with the standard casting method. There are many factors involved in determining whether parts should be thus fabricated, and these will be described at greater length in the section on limitations of the powder method.

With the advent of increased production for war purposes, the powder process has, in many instances, been utilized to insure a steady supply of many small parts needed for ordnance. The use of powder metallurgy has released machines and mechanics for other types of work, and because of the speed and ease of setting up for production, it has often been possible for suppliers of small parts to adhere to schedules they could not otherwise meet[33]. In addition, because of the low metal loss connected with the powder process, there is considerable saving of scarce or strategic material.

To the six general classes of materials listed above, can then be added another class that can best be described as utilitarian. The powder method has been used as an expedient to supplement and extend normal production methods without regard to cost. However, it has often proved itself to be economically competitive, and in many cases, bas effected considerable savings over normal production methods[33].

Tbe intensified war production schedules have opened the larger field that has been long predicted by powder metallurgists, that of using tbe powder method to displace the conventional methods of making many parts not in the classification of specialty products. Even under the abnormal war conditions, however, there are indications that progress along these lines will not be rapid and the early promise shown has not been completely realized. Progress has been made, nevertheless, but many of the developments and products are known only to those workers actually engaged in producing parts for the wartime program, and only when the story of the progress made can be told, will complete evaluation of the process be possible.

It is the belief of some metallurgists, as yet realized commercially with only a few special items, that parts can eventually be prepared by powder methods with properties superior to those obtained by melting, casting, and working techniques. At least one investigator reasoned that, since sintered tungsten is stronger than fused tungsten, iron or steel prepared similarly should show the same superiority[34]. Actual studies conducted using relatively high compacting pressures indicate that botb iron and steel can be prepared by powder methods with tensile properties better than those obtained on the some materials made by fusion processes.

Typical Powder Metallurgy Products

Most of tbe materials produced by powder metallurgy prior to about 1940 are well known; some have already been mentioned in this article, but for convenience are included in the following descriptions of typical products. Others of more recent development owe their immediate existence to the demands of wartime production, and, while some have been described in some detail in the technical literature, many have had only brief mention. Some typical parts made by powder methods are shown in Figures 1, 2, and 3.

1. *Cemented Carbides*[17,18,19,35]

Although tungsten carbide was produced many years ago and was found to be extremely hard, it was so brittle and low in strength that its use commercially where advantage could be taken of the bigh degree of hardness was not possible. About 20 years ago, it was discovered that the addition of a small amount of metallic constituent, such as cobalt, to the tungsten carbide powder would yield a hard, relatively strong compact after sintering. During the heating operation, there is partial melting with some solution of the carbide by the cobalt; and on cooling the cementing material produces the required strength.

The method of preparing the powders, compacting, and sintering has undergone considerable improvement since the first carbide materials were made. Essentially, in outline, the process consists of first preparing the tungsten carbide powder, mixing it with cobalt powder and ball milling the mixture until proper grain size is obtained and the carbide particles are coated with a thin layer of the cementing metal. In this treatment, other carbides are added as required. Following the milling operation, the mixed powders are pressed in suitable molds and given a pre-sintering heat treatment to increase the strength for bandling and to remove, by volatilization, lubricants which may have been used to facilitate pressing. After the pre-sintering operation, the compact can be cut to desired shapes quite readily. The sintering treatment which follows is carried out at about 1400°–1500° C. with the pressed parts placed in carbon boats or on carbon slabs and heated in a suitable neutral or reducing atmosphere. There is considerable shrinkage in dimensions in this sintering treatment which gives a product that is hard, dense, sound, and strong. Any further shaping is done by grinding or lapping operations.

The cemented carbides have many uses usually falling into the three general classes of die materials, cutting tool materials, and wear and corrosion resistant materials.

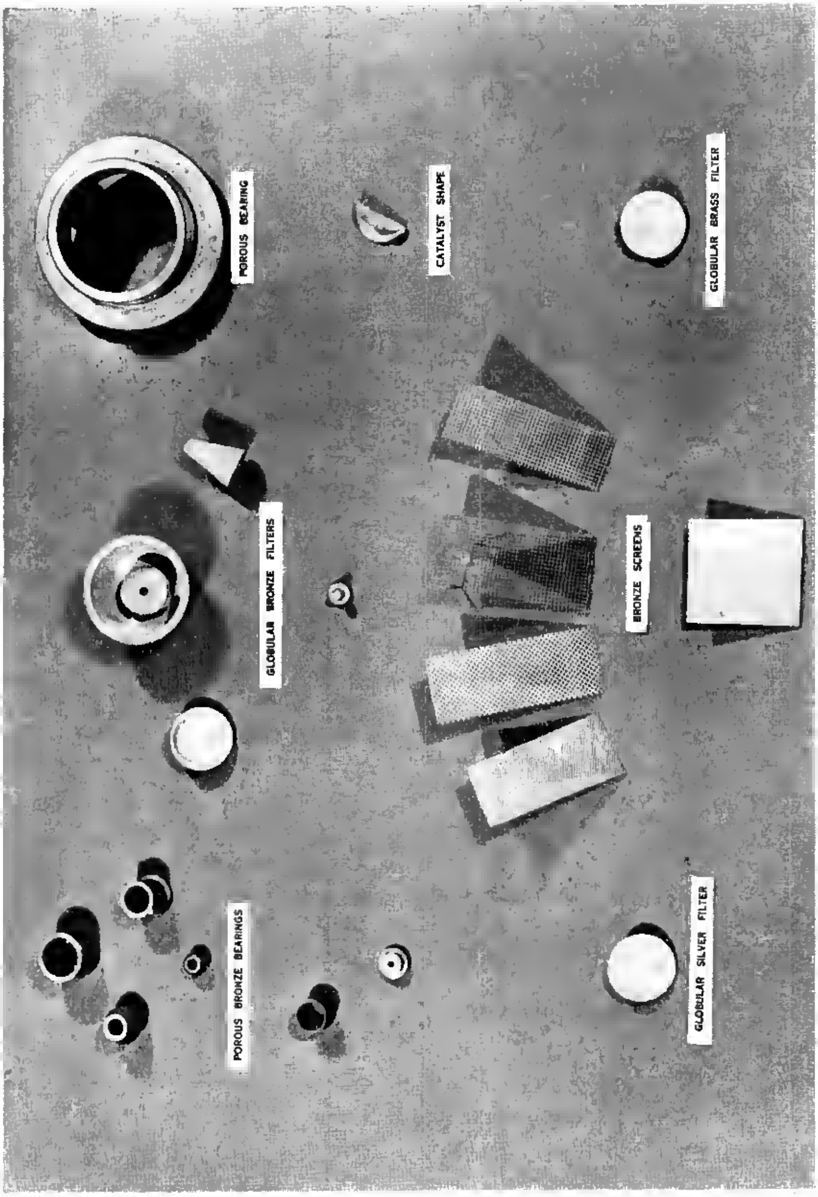

Fig. 1—Some porous parts made by powder metallurgy[23]

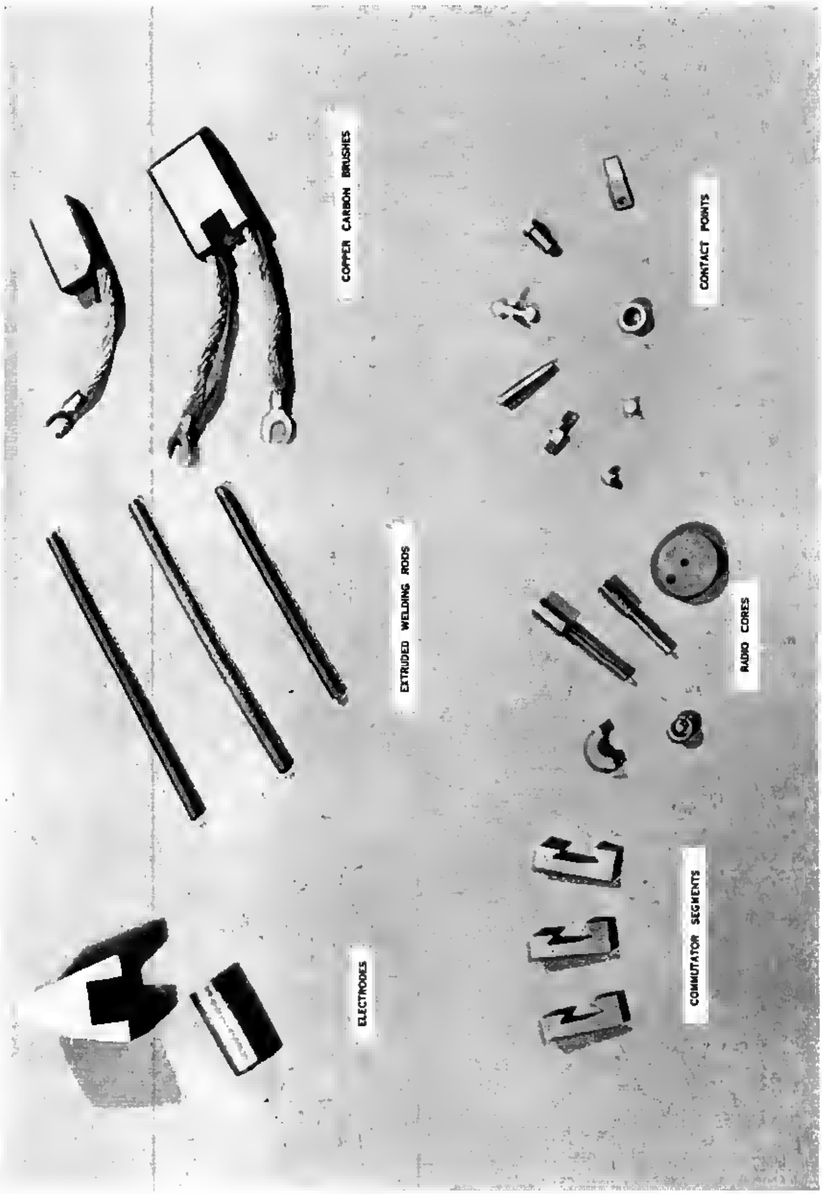

Fig. 2—Some electrical parts made by powder metallurgy[23]

Fig. 3—Some machine parts made by powder metallurgy[33]

The die materials are usually the simpler tungsten carbide compositions and can be used to advantage for extruding, drawing, sizing, and otber operations where the shape or dimensions of the article being worked is changed but where no metal is removed in the operation. The tungsten carbide can be used in this way for shaping many types of metals and alloys and this has been a major use of the product.

Cemented carbides, eitber the simple type or the mixtures, depending on the application, have been successfully used as cutting tips on a variety of tools, and for a number of different materials. This use has increased steadily due to the remarkable increase in production achieved. Decrease in cost of the tips and parts during recent years has further stimulated use.

Wear and corrosion resistant parts include gauges, guides of many types, pump valves for abrasive materials, sandblast nozzles, burnisbing tools and dies, and many others where utilization of the superior properties is indicated.

One use recently reported[36] has been that of cemented tungsten carbide for bullet cores in ammunition for anti-tank weapons used by the enemy in the desert warfare in Africa. The material has about twice the density of steel and is much harder, and, although not greatly resistant to shock under normal conditions, becomes quite effective under the high pressures attained during striking and penetrating armor plate.

2. *Porous Bearings*

Porous bearings, always a large runner in the powder metallurgy field, have been described in the section on the historical development. Where the bearings are impregnated with oil, there is usually sufficient to last the lifetime of the assembly, but provision can readily be made for supplying additional oil if needed by utilizing the capillary action of the interconnecting pores to draw oil from a reservoir in contact with the bearing wall. In such assemblies, there is always a film of oil for the shaft to run on in contrast to normal bearings where an oil film does not coat the shaft until run for some time.

3. *Motor Brushes and Commutator Segments*

Numerous types of current collector brushes are now made by powder methods. Copper powder can be added to the graphite mixture, and the desired part pressed and sintered below the melting point of copper to develop a strong, high conductivity brush of longer life for use against copper surfaces. Greater wear resistance may be obtained by adding zinc, tin, or nickel to the mixture. Improvement in operating smoothness may be attained by the incorporation of lead[14,23].

The brushes can be pressed around pigtail conductor wire inserts to insure good contact for the lead wire and eliminate attachment prohlems.

Commutator segments, resistance rings, and rotor bars in squirrel-cage motors, have heen successfully produced from copper by powder metallurgy methods[37].

4. *Refractory Metals*

Because of high melting points, tbe refractory metals, of wbicb tungsten, molyhdenum and tantalum are the most important, are prepared hy powder metbods. The preparation of each is similar, with the technique differing only in certain details where the characteristics of the individual metals require it[38].

Witb tungsten[39], tbe ore is treated by cbemical methods to yield pure tungstic oxide which is then reduced hy hydrogen at 650°–950° C. to give tungsten powder with a particle size range from 0.5 to 8 microns. As with other metal powders, care is exercised throughout to maintain high purity. After proper mixing and blending, the powder is compressed and tbe hriquette given a pre-sintering treatment at 1000°–1200° C. to give sufficient strength for further handling. The resulting bar is then clamped in electrodes in a suitahly designed hydrogen chamber, where acting as a resistance heater, heavy electric current is passed through it. The compact shrinks, the density increases, and a relatively solid bar results which can then be hot-worked. During the swaging or rolling, the working temperature can be gradually decreased until there is sufficient ductility by control of grain size to draw the material cold.

For tungsten used in lamp filaments, certain additions such as thorium oxide, or compounds of sodium or potassium mixed with such relatively non-volatile materials as SiO_2, Al_2O_3, or ThO_2 are intimately mixed with tbe tungstic oxide prior to reduction. These additions are effective in controlling grain growth and insuring proper grain boundary orientation for producing "non-sag" coiled filament. Essentially, the sodium and potassium compounds promote large grain growth while the others, such as tborium oxide, inhibit grain growth under the conditions of wire fahrication. When the material is drawn in wire form, the thoria particles form elongated stringers in the direction of drawing and tend to prevent grain growth across tbe wire wbile allowing exaggerated growth along the axis of the wire. The resulting structure of long grains with boundaries forming acute angles with the longitudinal axis of the wire is ideally suited for the coil type of lamp filament.

Molybdenum and tantalum are prepared in much the same manner as tungsten, although tantalum sintering and annealing must he conducted in high vacuum because of the ahility of the metal to absorh and retain gases at high temperatures.

5. *Heavy Alloy*

"Heavy alloy" is the name applied to a group of alloys composed of tungsten, copper, and nickel having a density of 16 grams per cc. or greater[40,41]. They were originally developed for fabricating the containers and nozzles for radium units, but have such interesting properties that a number of other uses have become evident. Specific properties depend upon the composition, but generally the tungsten comprises about 90 per cent of the alloy.

One of the best compositions claimed is that of 90 tungsten-7.5 nickel-2.5 copper which has properties as listed below:

Tensile Strength	90,000 psi
Yield Point	83,000 psi
Elongation in 1 inch	4%
Elastic modulus	32×10^6 psi
Brinell hardness	250–290
Density	16.3–17.0 gms. per cc.
Coefficient of expansion	5.6×10^{-6}
Thermal conductivity	0.25 c.g.s. units

The alloys are prepared by mixing the metal powders dry, adding a small amount of wax, in benzol solution, mixing until the solvent has evaporated, and then pressing to shape. The compact is heated slowly to about 1000° C. and then sintered at a higher temperature at which the nickel and copper particles fuse, and the tungsten is not only wet by the liquid, but actually dissolved. The fine particles are thus dissolved, but tungsten is reprecipitated on certain nuclei to develop large rounded grains. The solution and redeposition continue until the original fine tungsten particles are replaced by grains approximately 100 times the original particle diameter. The alloy thus consists of tungsten particles in a cementing phase of copper-nickel-tungsten.

There is a shrinkage of up to 20 per cent, and the resulting compact is relatively free of porosity.

The alloy has good machining properties and can be treated much like many cast alloys. It has good corrosion resistance and can take a variety of surface finishes.

In addition to its use in X-ray and radium work, its high density and strength make it attractive for use as a counterweight material in high-speed motor setups of many types.

6. *Electrical contacts and electrode materials*

Powder metallurgy can be utilized to fabricate material composed of two or more metals without any appreciable alloying so that the characteristics of each of the components may be retained to a large degree. This has opened a large field for electrical contacts and welding electrodes made by using compositions where the refractory nature of materials such as

tungsten, molybdenum, nickel, or graphite can be retained, while good electrical conductivity may be obtained with copper and silver[14,32,42].

Another type of material with good spark quenching properties is the combination of silver and cadmium oxide, which, because no alloying results, also has high electrical conductivity[43].

The contact materials may be made by any of the suitable powder techniques. One method is to press and sinter the powder composition sought, with or without final sizing or shaping of the part. Another method that is utilized for making tungsten-copper compositions consists in pressing a bar from tungsten powder and sintering at 1300° C. in hydrogen. The tungsten thus forms a strong porous structure which can then be impregnated with copper. This may be accomplished by placing the part in a graphite boat with copper, heating above the melting point of the latter, and allowing the voids to be filled by capillary action.[44]

No single contact material is satisfactory for all purposes, and a number of different combinations have been developed. These include silver-tungsten, copper-tungsten, silver-graphite, silver-molybdenum, cemented tungsten carbide, and copper-nickel-tungsten. They are used in many installations such as circuit breakers, welding machines, relays, and many types of industrial control equipment.

7. *Alnico magnets*

Many Alnico magnets of small size have been produced commercially by powder methods[45,46]. Magnets made in this manner are fine grained in contrast to the relatively coarse grained material obtained by casting methods. The material is uniform throughout with no cold shuts, cracks, blow holes or grain boundary segregation so that a more uniform flux density is obtained. Of particular interest are the close dimensional tolerances which can be maintained in the powder method and the small amount of grinding required in finishing. The composition can be held much more closely than for the cast alloy.

The process is limited economically to the production of small samples. Large samples can be prepared by conventional methods at a cost that would not allow sintered products to compete.

The presence of a highly oxidizable element (9–13 per cent of aluminum) presented difficulties when attempts were first made to prepare Alnico by sintering pressed compacts. To overcome this oxidation, the aluminum is added in the form of alloy powder of 50 aluminum-50 iron composition prepared by crushing and ball milling a casting of the brittle material[47]. In such form, there is practically no oxidation of the aluminum under the sintering conditions which prevail.

Another method to minimize or eliminate oxidation in sintering operations utilizes, in addition to the 50 aluminum-50 iron powder, approximately 2 per cent of titanium hydride incorporated in a powder mixture of aluminum-iron-nickel[48]. Decomposition of the hydride commences at about 450° C. with release of nascent hydrogen so that during the sintering operation, oxidation is prevented and part or all of any oxide already present may be reduced.*

8. *Metal filters and screens*

Related to the porous metal type of bearing and prepared in much the same way are the metal filters and screens made by powder methods[3,49]. Bronze, copper-nickel alloys, or pure nickel may be utilized, and porosities up to 80% by volume may be obtained. These filters have been used to advantage in the chemical industry for filtering strong alkaline solutions and other liquids of many kinds. One reported application is as a fuel filter 5 inches long and 2 inches in diameter for a Diesel engine[3].

Generally, the filter part can be bonded to steel or copper and made an integral part of the apparatus in which it is to function.

In the manufacture of the filters, the prosity can be accurately controlled. In addition to the methods of producing porous parts as previously described, a highly porous metallic mass can be prepared by sintering the component metal powders (sometimes with volatile additions) in the uncompacted condition using a protective atmosphere and a temperature determined by the type of powders used[50].

9. *Alloys having special properties dependent on close control of composition*

There are some alloys for special purposes where accurate control of composition and reproducibility of composition are of primary importance. Two such materials are: low-expansion alloys for metal to glass seals, and thermocouple wire for temperature measurement.

An alloy of 54% iron-28% nickel-18% cobalt having approximately the same coefficient of expansion as certain grades of glass is normally prepared by melting and casting procedures. This alloy can be prepared by sintering methods, however, with the same physical characteristics, but with closer composition control and less contamination[44].

Alloys of nickel-molybdenum and nickel-tungsten have been prepared

* The need for titanium hydride in the preparation of alloys of this type, and the effect of the hydride in controlling oxidation has been the subject of some discussion[48]. Its use is mentioned here only as a variation of the method described above and apart from any effects it may have on the magnetic properties of the alloys to which it is added.

by powder metbods for use as tbermocouple elements[44]. When these are used with nickel wire as the second element, the couples can operate at temperatures up to 1300° (Ni-Mo) and 1400° C. (Ni-W). Ease of preparation and not reproducibility of composition was probably the main factor in the fabrication of tbese two types of tbermocouple elements since the compositions reported are in the range wbere relatively large changes in composition produce little variation in thermoelectric voltage.

10. *Parts for Ordnance*

As bas already been mentioned, many powder metal parts are being manufactured for use in equipment of the Armed Services, and, while in some instances the parts are made by powder methods only because of expedience, it sbould be noted that, in all cases definite specifications must be met before acceptance, and a powder metal part tbat does not meet the rigid requirements has no more cbance of acceptance than has an inferior part made by other methods.

Among the parts whicb have been successfully produced are copper and brass rotating bands for projectiles[36]. While the cost of the powder metal bands is greater than that of bands made in tbe normal manner from copper or brass tubing, they compare favorably in actual performance in firing tests both as to bebavior on the projectile and wear on the gun barrel.

Improvement of the strengtb of porous metal bearings has been a factor in their adoption for use in anti-aircraft guns where tbey may operate under severe conditions. It has been reported that 100 parts are thus utilized in a single gun installation[51].

Another item reported to be in production is an iron powder part of an elevating hand mecbanism for both the .30 and .50 caliber anti-aircraft machine guns[36]. Knurling of the outer surface of the ring part and the marking off of degrees are performed on the part in a coining blow.

11. *Sintered Iron Parts*

Prior to the wartime demands for sintered iron parts, tbere had been developed a fairly extensive field for peacetime uses particularly in the automotive industry. Bearings bad been manufactured for some time and, following this, production bad extended to the fabrication of oil pump gears, door catcbes, cams, and other parts where very bigb strength is not essential. In general, these sintered iron parts bave mecbanical properties similar to tbose of cast iron, but considerable range in properties may be obtained by proper selection of raw material and treatment. Grad-

ing of parts from iron powder into tbree classes according to tbe type of product and properties has been outlined as follows[52,53]:

Type A Materials baving mechanical properties similar to ordinary cast iron suitable for applications where stresses are very low.

Type B Materials similar to Type A hut having improved tensile strength, a definite yield point, and a noticeahle elongation.

Type C Materials having mechanical properties approaching ordinary malleable iron, suitable for applications where stresses, including impact, are moderate.

Prior to 1941, the iron powder used commercially for pressed and sintered parts was of Swedish origin because that was the only powder available in quantity, quality, and at a price which allowed competition economically with established methods of production. Domestic iron powders are now available, however, that are superior to those formerly imported.

Of the sintered iron products manufactured in this country, an interesting example is a small gear for automohile oil pumps[27]. This gear was formerly made by machining cast iron blanks but was adapted for powder metal production because of greater ease in fabrication at less cost and more satisfactory operation. The gear teeth must be true involute curves with surfaces such that noisy operation and hinding are prevented. All of these characteristics can be readily obtained by pressing and sintering, while more difficulty is encountered with cast gears because of the intricate machining work involved. The sintered gear avoids tbese expensive machining operations, and the teeth have so much better surface finish, and mesh so accurately, that noisy operation is avoided. In addition, the associated porosity is helpful in that oil impregnation assists in smoother and quieter operation.

The pressed gears are lighter in weight than the cast gears, and wbile the mechanical properties are not of high order, they are satisfactory for the use.

12. *Cladding and Duplexing*

Powder methods are useful in cladding, duplexing, or any of the processes whereby one metal or alloy may be coated with another for protective purposes, to obtain special properties as in bimetal strip, to obtain hard surface layers on strong, tough hacking material, or to obtain a thin layer of relatively high-cost metal of desirahle properties on a suitahle low-cost backing strip.

For fahrication of bimetal, layers of the respective component metal powders may be placed in the die in the desired proportions and compacted. Upon sintering, an alloy bond is formed between the layers, and the briquette

may be rolled or otherwise worked to the desired thickness[50,54]. An advantage of this type of bimetal fabrication is the use of alloy bonding at the interface instead of a solder which might limit the operating temperature of the material[14].

13. *Metallic Friction Materials*[14,55]

The ordinary type of friction material for brake linings, clutch facings, and similar uses is generally composed of asbestos with an organic type of binder. Under normal operating conditions, this type of material is quite satisfactory, but where severe conditions of operation are encountered, the heat generated at the braking surfaces may be sufficient to decompose the binder and cause rapid wearing of the friction facing.

By powder methods, however, a metallic matrix can be formed with admixtures of friction producing ingredients to give a facing that is capable of withstanding the high temperatures generated under severe operating conditions. The exact composition of the facing is determined by the requirements, and a number of different metallic and non-metallic materials are used. Generally, however, the basic ingredient of the matrix is copper to which may be added such modifying metals as tin, lead, zinc or iron. The friction-producing powder is generally an abrasive such as silica or emery which is varied in amount according to the coefficient of friction that is desired.

The metallic elements may constitute only about 50 per cent of the part by volume with the other 50 per cent represented by non-metallic ingredients and pores. In consequence, therefore, the facing is weak and brittle and is usually bonded to a strong backing plate.

The friction materials are prepared in the normal manner by mixing suitable powders, compressing in suitable form, (usually as thin annular rings) and sintering. The sintering operation is generally performed so that the part is bonded to the backing plate at the same time. Finishing operations are then performed to adjust the facing to size and proper shape for use.

14. *Cores for Inductance Coils for Telephone and Radio*[56,57]

Although the manufacture of cores for induction coils for telephone and radio use does not fit into the field of powder metallurgy as more strictly defined in the Introduction, the procedure is in many ways so similar to the processes described above, and the product of such interest, that a brief description is included in this review.

The coils in communication circuits may operate over a wide range of frequencies from voice frequencies up to millions of cycles per second.

By the use of a finely divided magnetic powder, the particles of which are insulated from one another, the eddy current losses in the cores can be reduced to a level low enough for satisfactory use.

The first metal powder used for cores in the telephone industry was electrolytic iron. This was later superseded by more suitable magnetic materials such as the permalloys.

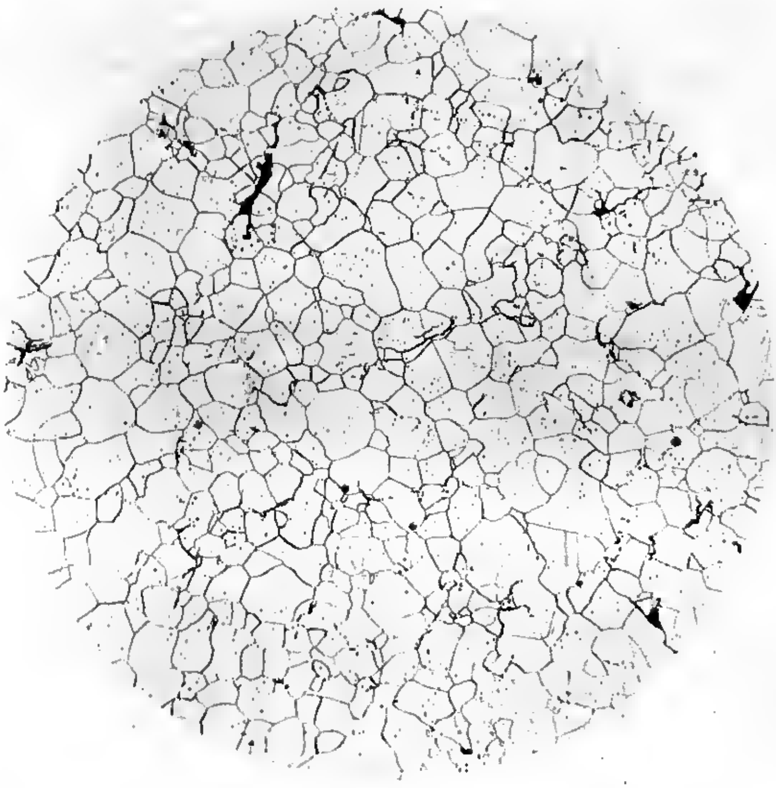

Fig. 4—Brittle molybdenum-permalloy, as rolled to produce fine, equiaxed grain. Magnified 130 diameters.[57]

The procedure utilized to obtain the permalloy powder is worthy of note. Ingots of the desired composition are prepared by melting and casting in the normal manner with, however, the addition to the melt of a small amount of sulphur which acts as an embrittling agent to facilitate pulverization. The sulphur exists as microscopic films of complex sulphides at the crystallite boundaries. At normal temperatures these films are brittle, but at elevated temperatures are either malleable or dissolve in

the iron-nickel solid solution. The alloy can therefore be hot-rolled to small section under controlled conditions to develop a desired grain size, and then cold-worked to separate the individual crystals. Grain size depends upon the degree of refinement in the hot-rolling operation and upon the distribution of the sulphide film around the grain boundaries. Final pulverization is accomplished in an attrition mill, and the product is generally annealed to soften the particles.

The powder is then treated to cover each of the particles with an insulating film that is generally of the ceramic type. The cores are then pressed at about 100 tons per square inch to develop proper density and strength. There is no sintering treatment performed on this type of material after pressing, but the cores are generally annealed to remove pressing strains and restore magnetic quality.

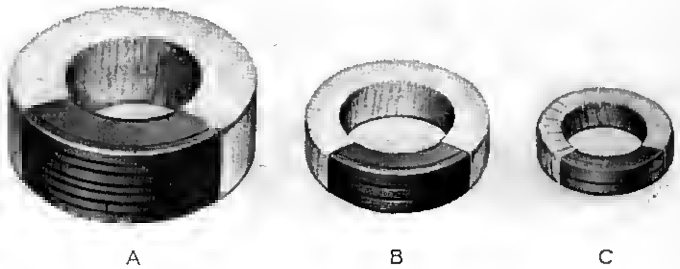

Fig. 5—Relative size of cores for a given duty in a telephone circuit. A is a core made of electrolytic iron powder; B is made of 80% Ni-permalloy powder; C is 2-81 Mo-permalloy.[65]

This powder metal process is thus different from those previously described and is one of the specialty group of materials which cannot be prepared by any other methods. Except for the deliberate coating of the metal particles with an insulating film, and the avoidance of a sintering operation, however, the procedure is that normally followed in preparing powder metal articles.

In addition to the permalloys described, a number of other magnetic powders are used in pressed core form for various applications. These include electrolytic iron, carbonyl iron, and several types of magnetic oxides. Carbonyl iron, in particular, has been used extensively for radio cores where the spherical shape and small size of the particles have been factors in their successful utilization.

Advantages of the Powder Metallurgy Process

Throughout this paper, numerous advantages of the powder metallurgy process have been indicated as well as some of the limitations. Outlined

below in somewhat more detail are these considerations and others which enter into an evaluation of the process as a whole. In those instances where a product cannot be made in any way except by powder methods, evaluation is easy. But for those products which must compete with standard methods of fabrication, the problem is more complex, and generalizations cannot always be applied.

The following are some of the advantages of the powder metallurgy process:

1. High purity of the metal content of the finished product can be maintained. Control of the manufacture of the powders enables producers to supply metals that generally run well above 99 per cent purity, and often as high as 99.99 per cent for some metals such as tungsten, tantalum, and zirconium[23]. Opportunity for additional impurity pickup is slight under the conditions prevailing in the pressing and sintering operations, so that the original metal purity is retained, and may even be improved by oxide reduction or removal of volatile impurities.
2. Composition of the product can be accurately controlled and reproduced[30,44]. There are no losses due to oxidation or slagging as in melting processes so that the metal content can be quite readily fixed.
3. Structures, alloys, or materials not possible of fabrication by any other method can be produced by powder methods[29,30,49,58]. These have been adequately described and include porous bearings, sintered carbides, refractory metals such as tungsten and tantalum, and combinations of metals, and of metals and non-metals that do not alloy.
4. High production rates[58,61,65], especially on small parts, can be attained by use of automatic presses of the pill tabletting type and of continuous type sintering furnaces. One order of forty million small parts required by the Navy was produced at the rate of 520 pieces per minute by powder methods[64].

   Larger size articles cannot be produced at any such rate because of press limitations which may necessitate hand operation, but with pressed iron parts, high rate of production is one of the factors that allows the process to compete with other standard methods of manufacture.
5. A wide range of certain physical properties can be obtained for any particular material being fabricated[58,62]. Control can be exercised over such properties as density, porosity, grain size, and strength by variation of the type and size of powder particles, die pressure, and sintering time and temperature.

   In some instances such as small Alnico magnets, structures devel-

oped may have better mechanical properties than the same material in cast form[44,45,46,47]. The same type of fine-grain structure developed in laboratory samples of iron parts compacted at high pressures and sintered at relatively low temperatures also exhibit superior tensile properties[34].

6. The powder method of manufacture may be more economical in many instances due to factors such as rapid quantity production, lower labor costs, ease of setting up for manufacture, conservation of material, and elimination of machining operations[30,62]. A reported instance of analysis of the normal cost of producing approximately one hundred different units used in a piece of Ordnance equipment revealed that powder metal parts effected a saving of about 70 per cent[33].
7. Rather close dimensional tolerances[30,58,61] on small or medium size parts up to about two inches major dimension can be secured, averaging ±0.001 inch. Closer tolerances of ±0.0005 inch are attainable and may be even smaller on special production jobs. On larger parts, the tolerance may be in the order of ±0.002 inch. Frequently, however, accuracy of dimensions is attained only through a coining or re-pressing operation of the sintered part.
8. There is usually very little material waste associated with powder metal parts manufacture since there is little or no scrap loss[23,58,62]. Powder losses generally run below 0.5 per cent[59]. In melting and casting operations on small parts, on the other hand, the sprues and risers may be several times the weight of the finished casting. In addition, machining operations on cast parts may remove from 10 to 50 per cent of the metal, and while most of it is recoverable as scrap, it represents a loss in the manufacturing process[62].
9. Highly skilled labor is not required for most operations in the powder method[33,59]. Except for the construction of the necessary dies and die parts, semi-skilled labor may be used. This is of value in industrial plants producing parts for Ordnance because skilled mechanics who would normally be required for machining operations can be made available for other work.
10. Tooling costs are relatively low in comparison with other high-production methods, and less time is usually required to set up for production[33]. Secondary operations such as machining of the sintered products may be eliminated or greatly reduced.

Limitations and Problems of the Powder Process

As has been indicated in several sections of this review, there has been a recent shift in emphasis in the type of product made by powder methods,

and in addition to those materials that are difficult or impossible to make by other methods, parts are now being manufactured in direct competition with those made by conventional, established procedures.

Under these circumstances, economy of production, in addition to technical feasibility, becomes a major factor in the utilization of the process. Of the numerous limitations of the process, some are inherent and definitely limit its application while others are incidental and susceptible to certain measures of control. The more important of these limitations and problems are outlined below:

1. The cost of metal powders is high in comparison with metal for other methods of producing similar parts, and availability of suitable powders is another problem[44,63]. Both cost reduction and availability have received considerable attention in recent years, and with increased use of metal powders and the large-scale powder production entailed, substantial price reductions have been effected and a wider variety of types of powder have been made avilable. The development of domestic sources of supply of a satisfactory low-cost iron powder to replace Swedish sponge iron is an example of a successful attempt to overcome a limitation of the process[63].
   In a final analysis, metal powder costs must be balanced against overall costs before a raw material cost standard can be set up.
2. Die expense[14,44,61,63] is high, especially for large and complicated parts and for high pressures. New dies are required for each part of different shape and size, and each die must be installed and carefully adjusted for operation. With the entry of the powder metallurgist to the low cost part field, there will be need for more complicated dies to meet the competition of intricately shaped parts produced by casting methods. The tool cost, however, for the powder process is generally lower for a given part than with other processes. Die cost may range from about $150 for small simple parts up to $1800 or more for large parts or complicated shapes[33].
3. Sintering furnaces pose many problems in the production of powder metal parts[14]. Close temperature control and uniformity are essential for control of dimensional changes in compacts. The fabrication of iron or alloy steel parts requiring higher temperatures than have been previously utilized in the industry add to the difficulties of furnace design.
4. The size and form of powder metal products is limited[44,62,63]. Large samples require huge presses to obtain the desired compacting pressures and both tool and press costs increase. Increase in size of compacts leads to a non-uniform distribution of pressure and may adversely affect the shape and dimensions of the article in the sintering

operation. Large presses are usually not of the automatic type, which means hand operation with lower production rates and increased cost. Low apparent density of most metal powders affects die design and limits the thickness of parts produced. A compression ratio of about 3 to 1 is generally assumed, which means mold depth must be at least 3 times the thickness of the finished compact. Other factors of die design are noted under item 7 of this section.

5. The powder process is essentially one of mass production, and a reasonable number of parts must, in general, be fabricated or the costs per unit will be excessive.
6. On a production basis, powder metal structural parts generally have relatively low elongation, tensile strength and impact strength[14,44,63]. The mechanical properties of a sintered part depend to some extent on its density, which itself is a function of the type of powder used, the compacting pressure, and the sintering treatment. Because of the voids normally present in powder metal parts, the ultimate properties cannot be expected to be as good as those obtained on cast and wrought materials[62].
7. There are a number of design limitations for powder metallurgy parts[11,44,61,62].
   a. Sharp corners should be avoided and internal angles should have fillets.
   b. Large and abrupt changes in thickness of parts should be avoided, as should uneven cross sections.
   c. Re-entrant angles, grooves, and undercuts cannot be molded, and if required, must be machined in an extra operation. Internal and external threads, and holes at right angles to the central hole or perpendicular to the axis of pressing, likewise cannot be pressed, and must be machined.
   d. Length of pressed parts must be comparable to the cross-section area because of pressing limitations. A long section may have a soft central portion of low density.
   e. There is almost no flow of metal powders during compacting because of friction between particles, and between particles and the die walls[60,62].
8. Although powder parts can be produced to close dimensions by careful control of the compacting and sintering operations and by coining or re-pressing the sintered pieces, tolerances should, in general, be fairly liberal if costs are to be kept down[14,61]. Close dimensional tolerances may necessitate machining operations to meet specifications. Eccentricity of cylindrical parts may be controlled fairly closely, but concentricity may be troublesome because there must be clear-

ance between die parts and plungers, and the clearances may be cumulative[60].

9. There is a lack of technical information available for engineers and designers. Tests on metal powders and finished parts have not been standardized, and until such standardization has been achieved the metal powder consumer and the ultimate user of the sintered parts have no check on the respective products. This situation is now being remedied.
10. There are some thermal limitations that may cause difficulties in the sintering process in certain instances[63]. Some oxides can be reduced only at temperatures above the melting point of the metal itself and prevent effective welding of the powder particles.
11. Metal powders in a fine state of subdivision are readily combustible and must be treated as potential fire and explosion hazards[20,62]. Zirconium, magnesium, aluminum, and titanium are the most inflammable with iron, manganese, zinc, silicon, tin, and antimony, moderately inflammable. Precautions must be taken to keep dust out of the air in the mixing and pressing rooms, not only because of the explosion hazard, but also because of possible toxic effect on workers.
12. Deterioration of metal powders may occur in storage due to oxidation or absorption of moisture with subsequent chemical reaction to change the composition[62].

Conclusion

This correlated review of some of the more common aspects of powder metallurgy is presented to provide information on an increasingly important production method. The review makes no pretense of complete coverage of the subject, and many important topics such as hot pressing, press and furnace design and operation, sintering atmospheres, and die design and operation have not been described. These and other more specialized topics that are beyond the scope of this paper may be found in the appended list of references.

Acknowledgment

The authors have drawn freely from many of the articles on powder metallurgy published during the past ten years. Wherever possible, reference is made to the original source of the topic material or to associated articles where more complete information may be found. To these sources listed below, the authors are indebted for much of the material presented in this review.

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